

# Indirect Searches for Dark Matter with the Fermi Large Area Telescope

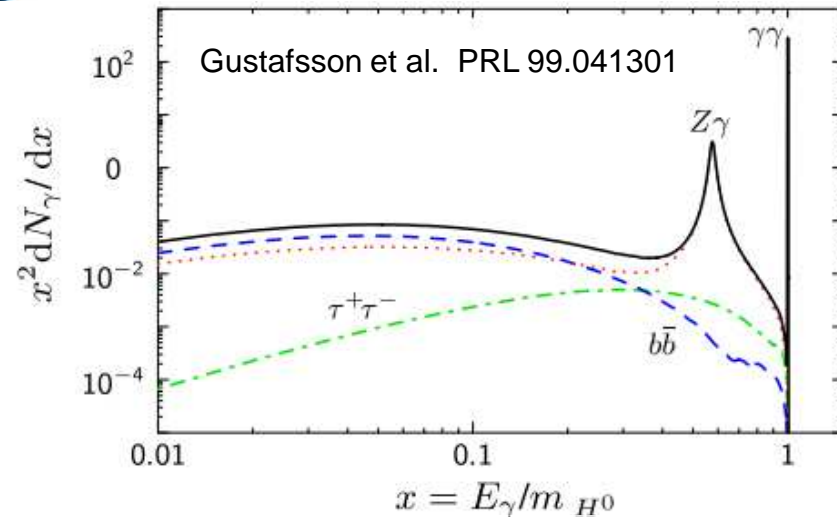
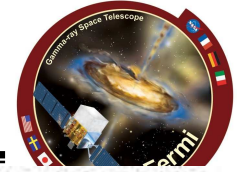
**Andrea Albert (SLAC)**

**On Behalf of the Fermi-LAT  
Collaboration**

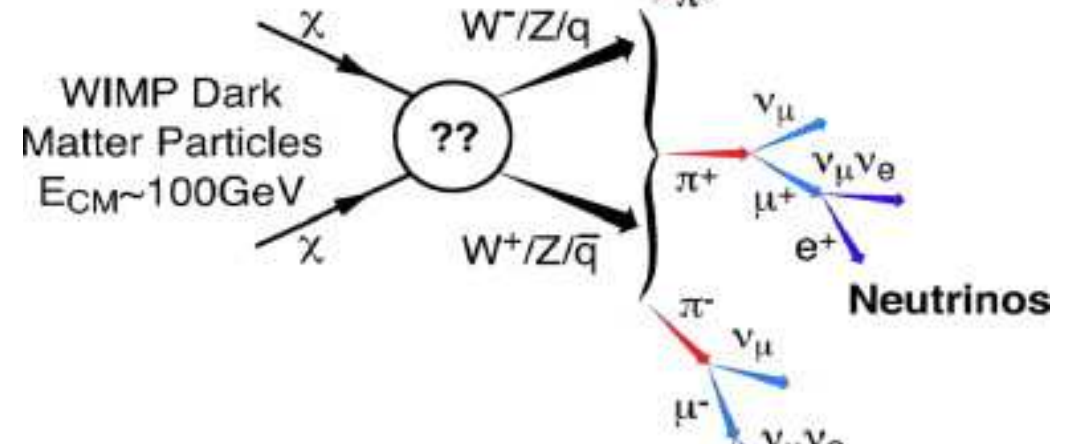
**TAUP**

**Sept 12<sup>th</sup>, 2013**

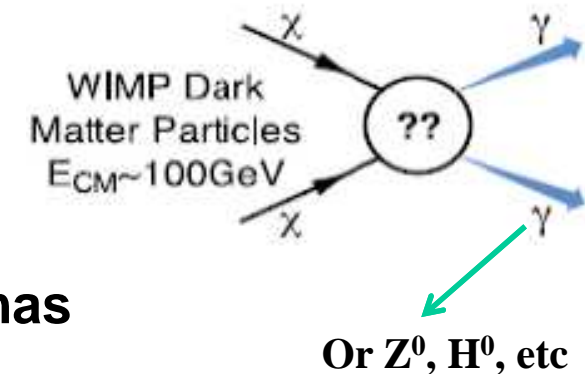
# Gamma-rays from WIMPs



Broad, continuum



Spectral Line



- **WIMP = Weakly Interacting Massive Particle**
  - DM candidate (e.g. neutralino)
  - Believe the Milky Way sits in a large spherical “halo” or cloud of DM
    - **Non-relativistic (cold) DM**
- **WIMPs annihilations (decays) may produce gammas**
  - Dominant channels -> broad continuum
  - Monochromatic channels expected to be rare (loop-suppressed)



## Public Data Release:

All  $\gamma$ -ray data made public  
within 24 hours (usually less)

## Si-Strip Tracker:

convert  $\gamma \rightarrow e^+e^-$   
reconstruct  $\gamma$  direction  
EM v. hadron separation

## Hodoscopic CsI Calorimeter:

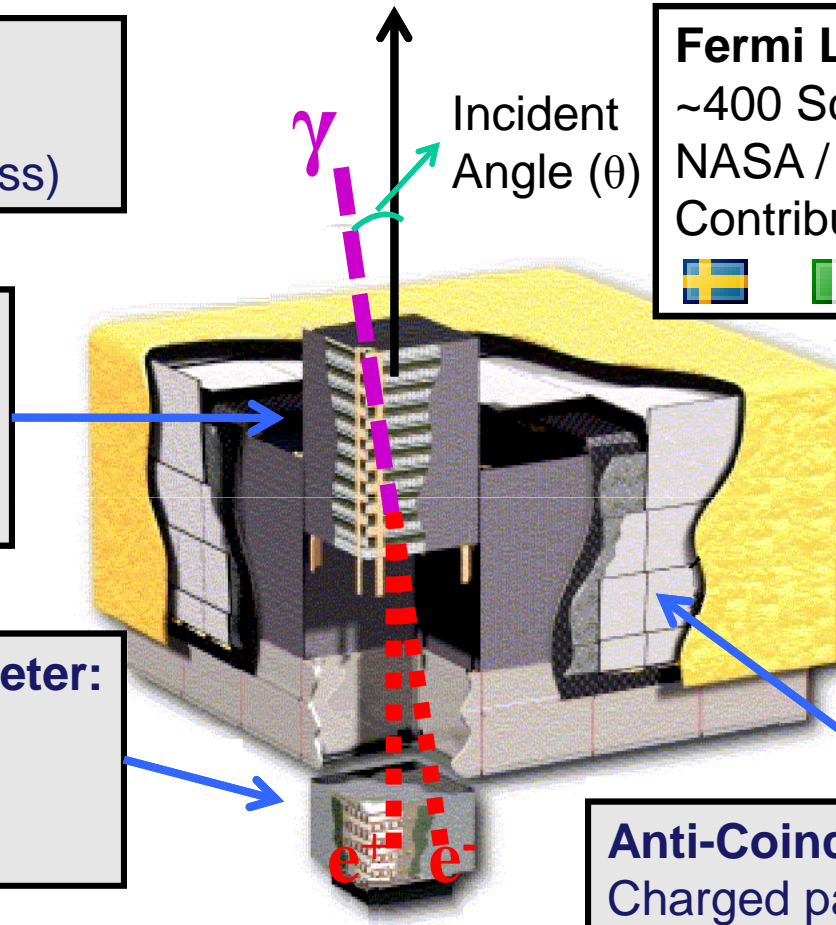
measure  $\gamma$  energy  
image EM shower  
EM v. hadron separation

## Trigger and Filter:

Reduce data rate from  $\sim 10\text{kHz}$   
to 300-500 Hz

## Fermi LAT Collaboration:

$\sim 400$  Scientific Members,  
NASA / DOE & International  
Contributions



For detailed description  
of LAT performance  
see arXiv: 1206.1896

## Anti-Coincidence Detector:

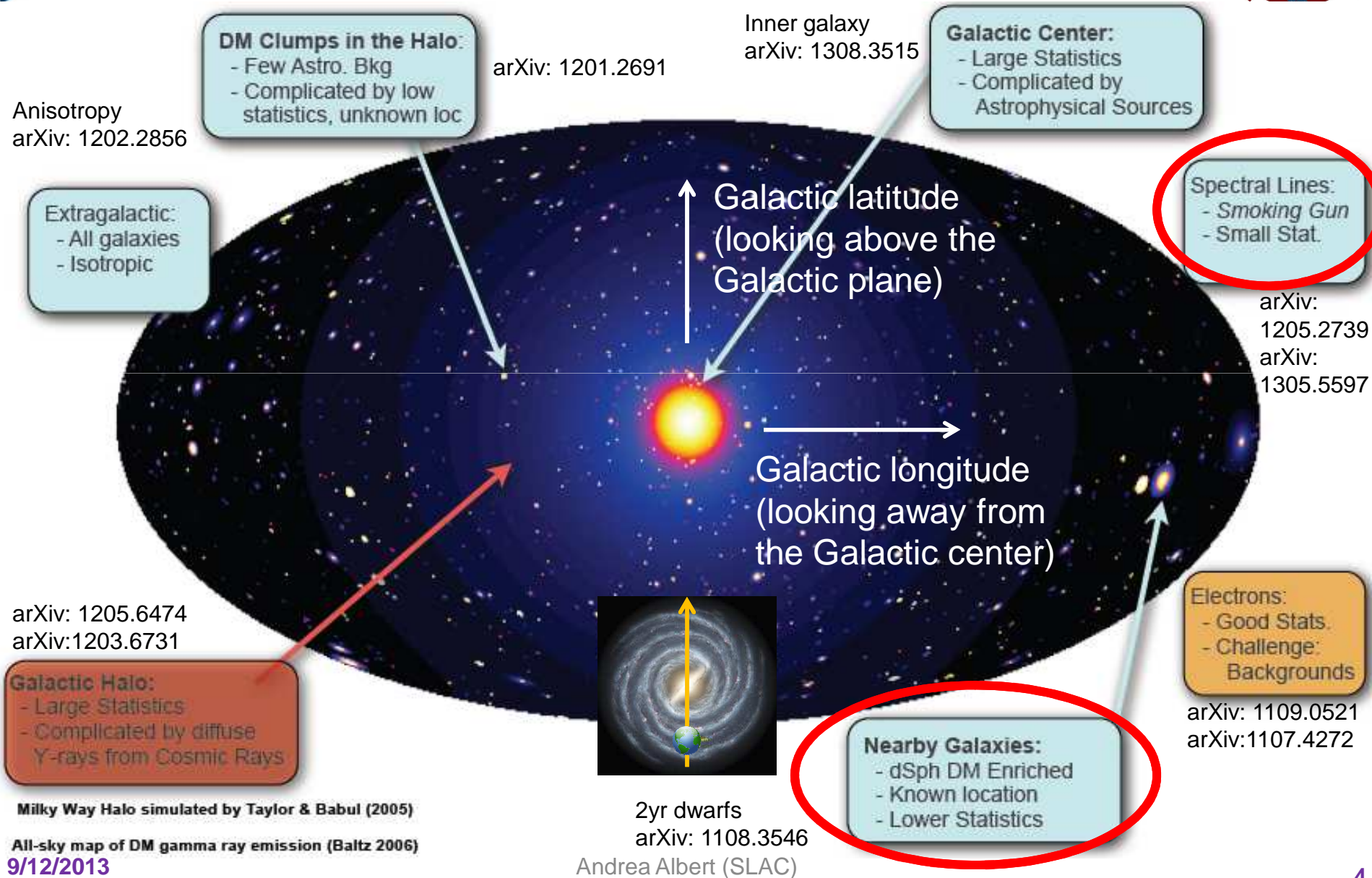
Charged particle separation

## En Range and Coverage:

20 MeV to  $>300$  GeV  
See whole sky every 3 hrs



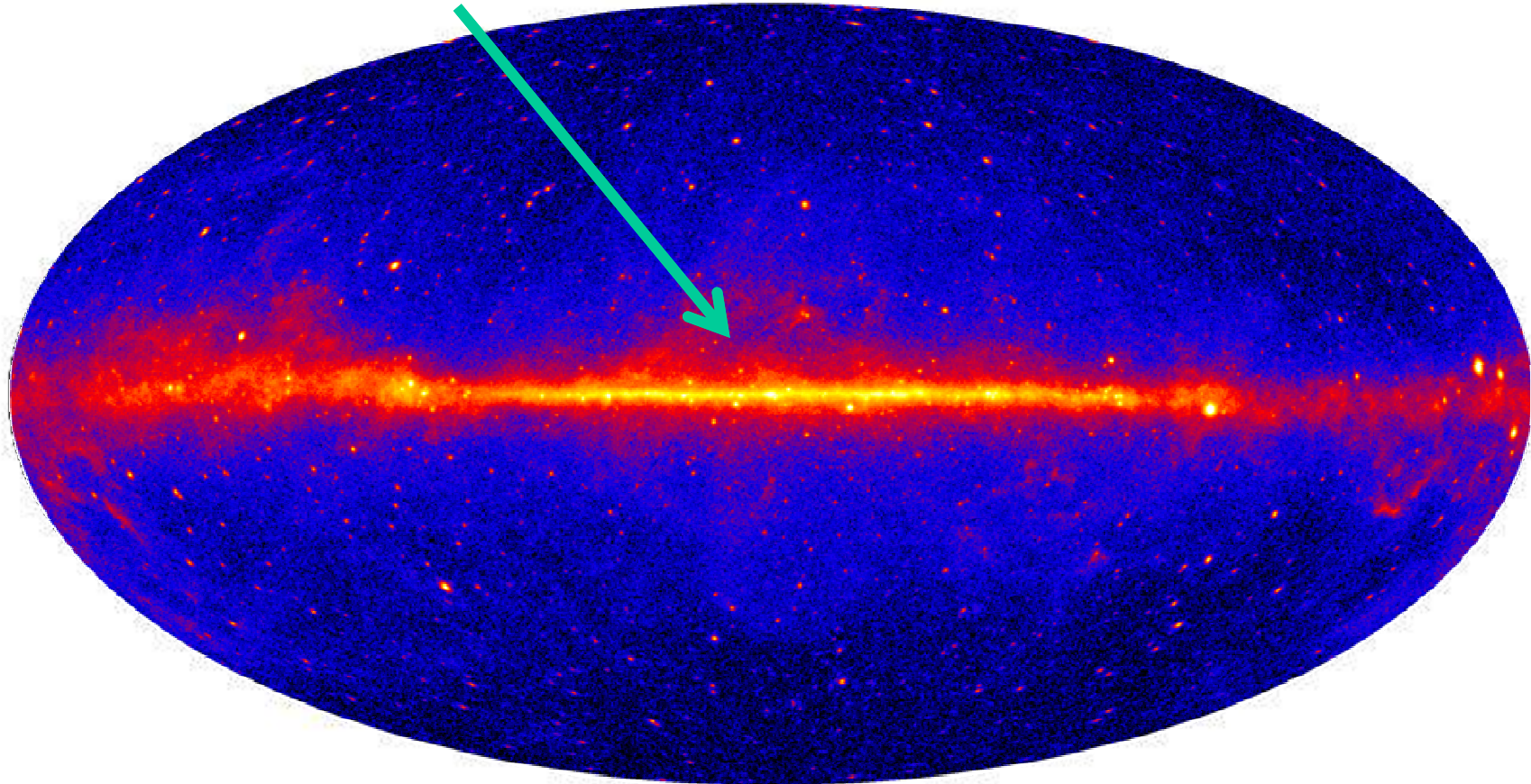
# Galactic Distribution of DM



# Large Astrophysical Background



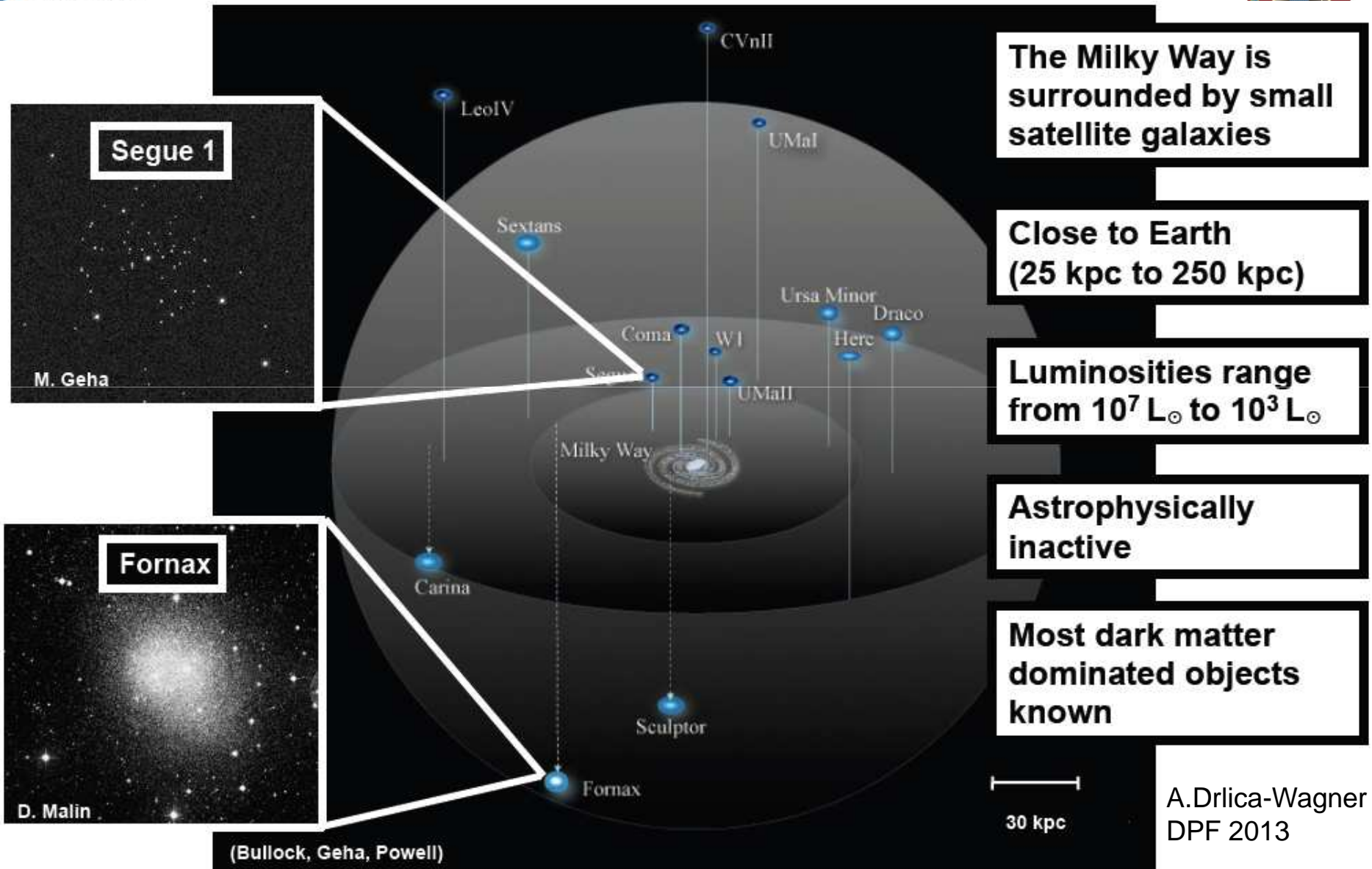
**Smooth component peaked in Galactic Center  
(central cuspiness has large uncertainties)**



Milky Way Halo simulated by Taylor & Babul (2005)  
All-sky map of DM gamma-ray emission (Baltz 2006)



# DM Search in MW Dwarf Galaxies

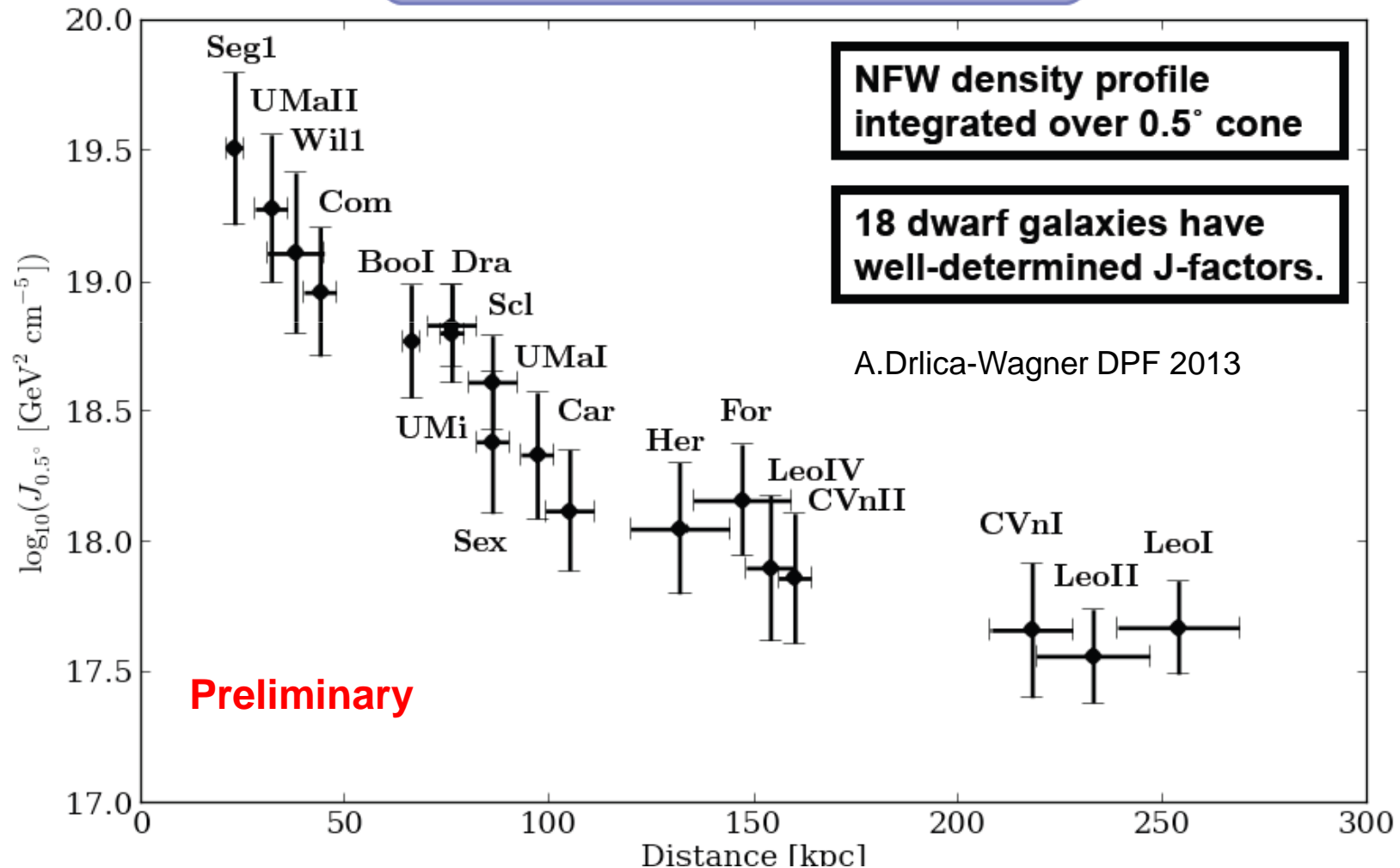


A.Drlica-Wagner  
DPF 2013

# J-Factors for Dwarf Galaxies



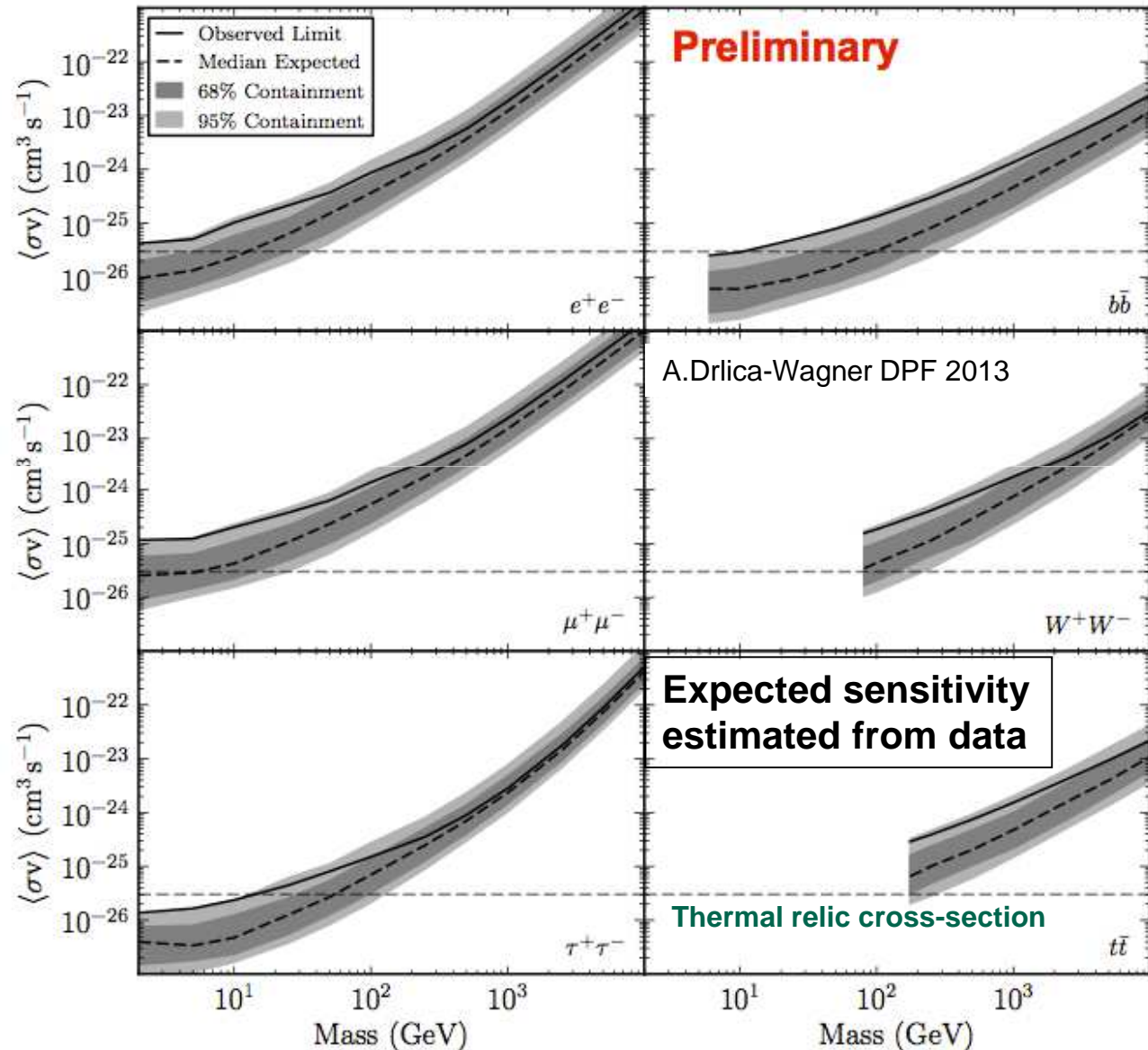
$$\int_{\Delta\Omega(\phi,\theta)} d\Omega' \int_{los} \rho^2(r(l,\phi')) dl(r,\phi')$$



# Combined dSphs Results

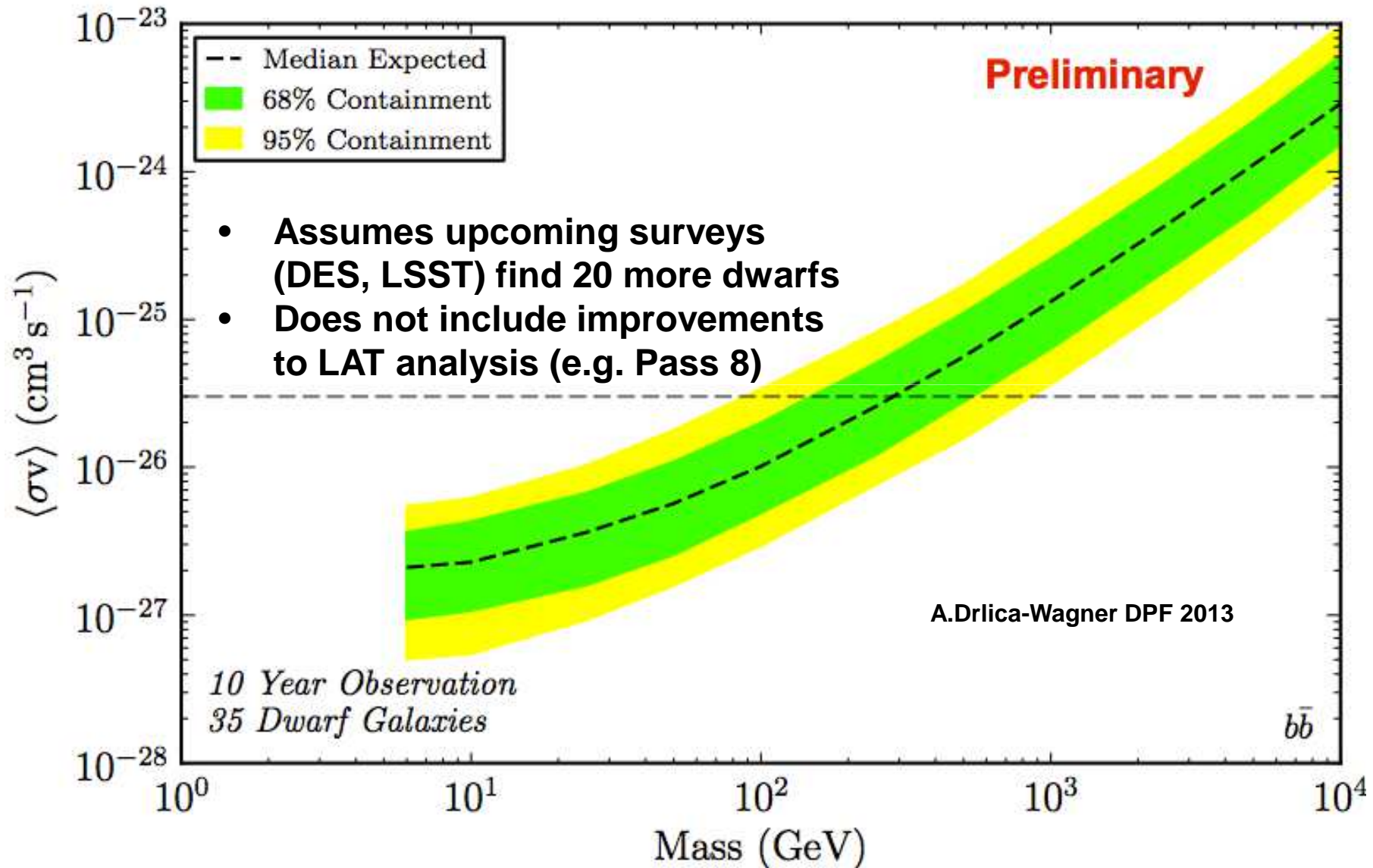


- Joint likelihood analysis of 15 dwarf galaxies
- 4 years of data in energy range 500 MeV – 500 GeV
- Account for uncertainties in J-factor
  - DM distribution determined using observed stellar velocities
- 6 annihilation channels considered
- No DM seen
  - Exclude canonical thermal relic cross-section for masses less than ~10 GeV (in  $b\bar{b}$  and tau's)





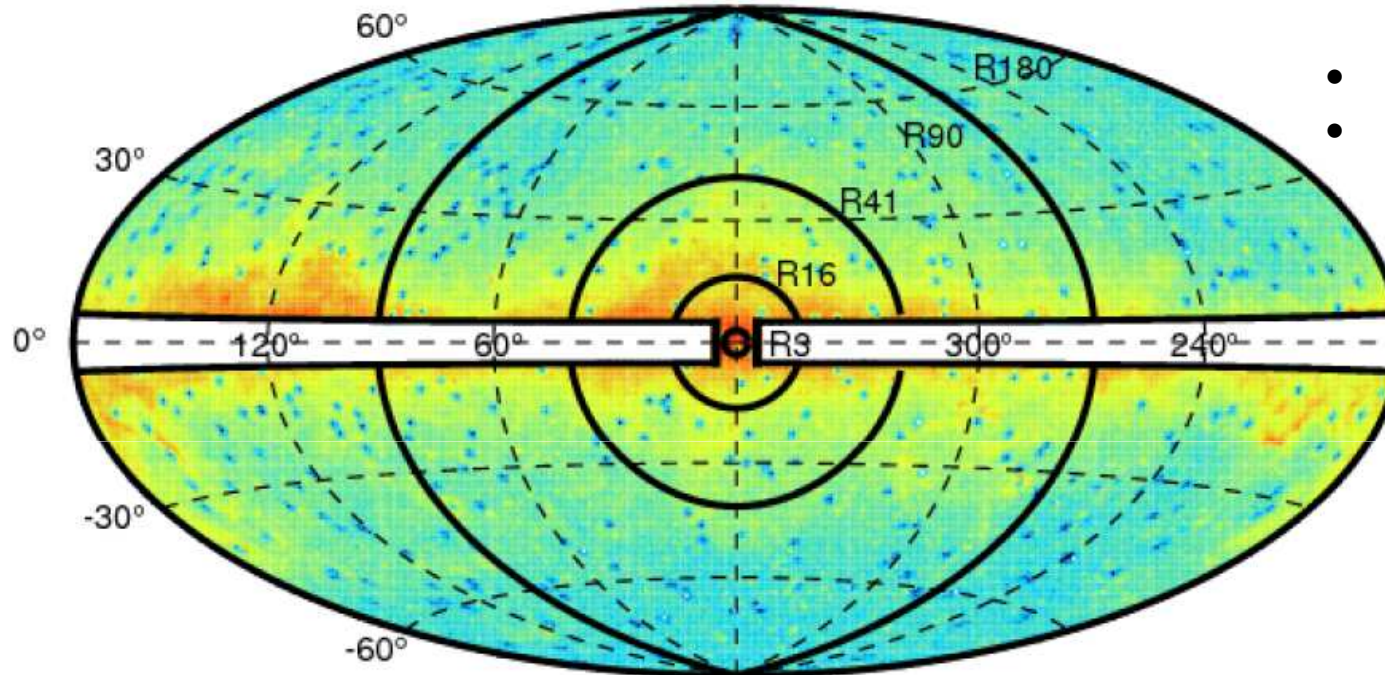
# Projected Limit Improvement with dSphs



# Search for Spectral Lines



## 3.7 year Counts Map

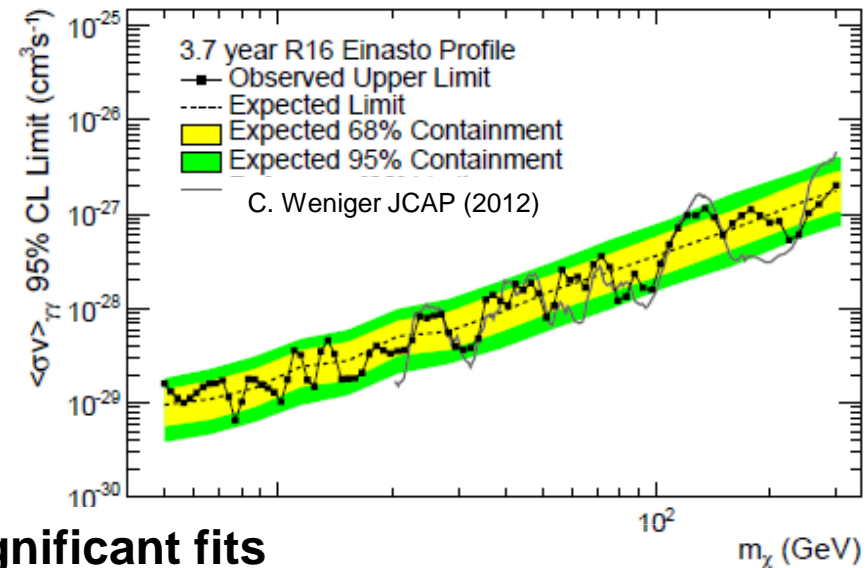
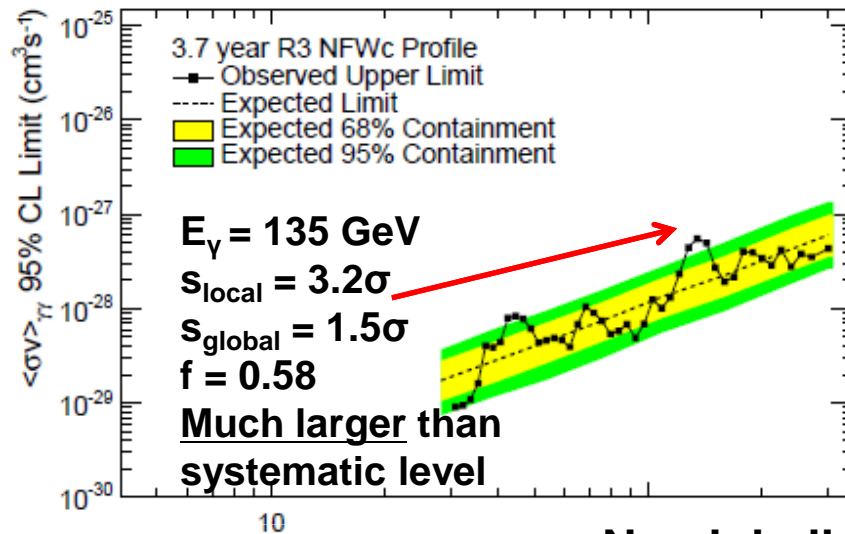


- R3 (contracted NFW, no src masking)
- R16 (Einasto)
- R41 (NFW)
- R90 (Isothermal)
- R180 (DM Decay)

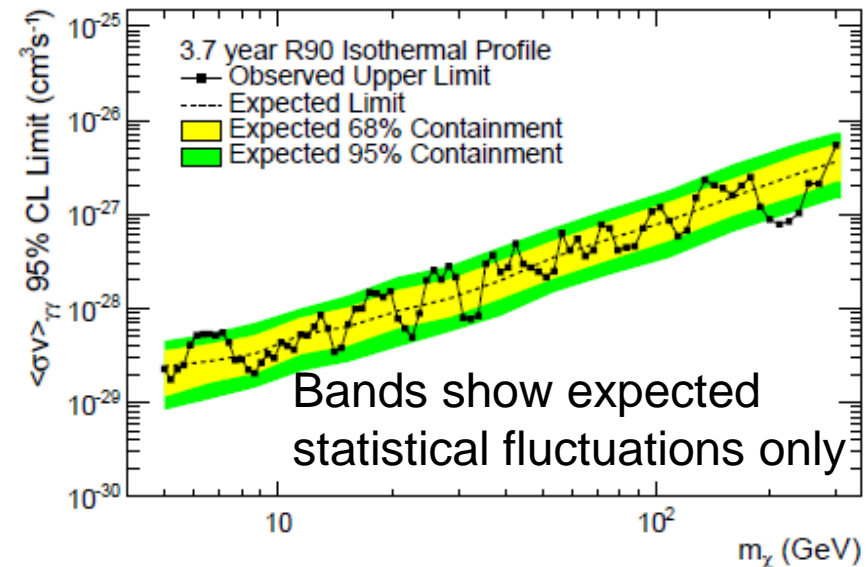
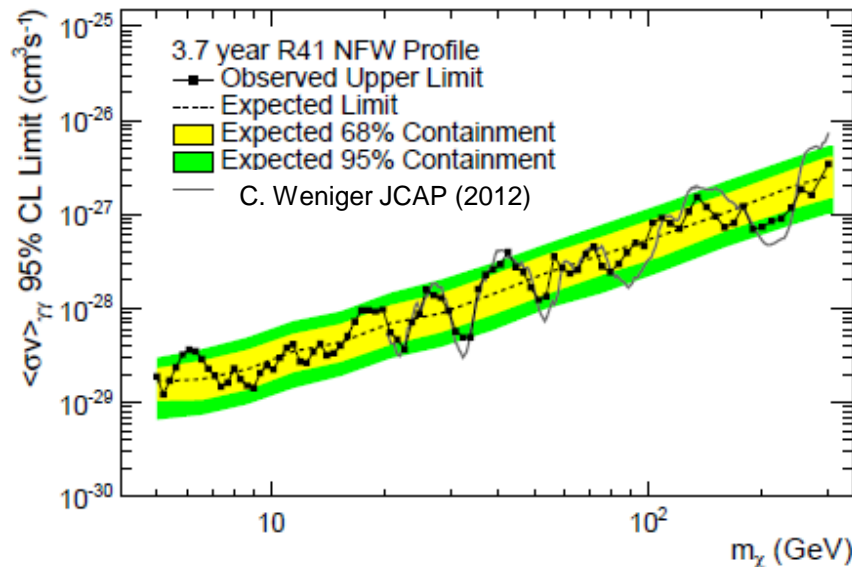
ROI optimization motivated by Bringmann et al 2012 (arXiv:1203.1312) and Weniger 2012 (arXiv:1204.2797)

- Search for lines from 5 – 300 GeV using 3.7 years of data
  - Maximum likelihood fit with improved energy dispersion model
- Use P7REP\_CLEAN event selection
  - Reprocessed data with updated calorimeter calibration constants
  - Clean cuts are recommended for faint diffuse emission analysis
- Mask bright ( $>10\sigma$  for  $E > 1$  GeV) 2FGL sources

# 95% CL $\langle\sigma v\rangle$ upper limits

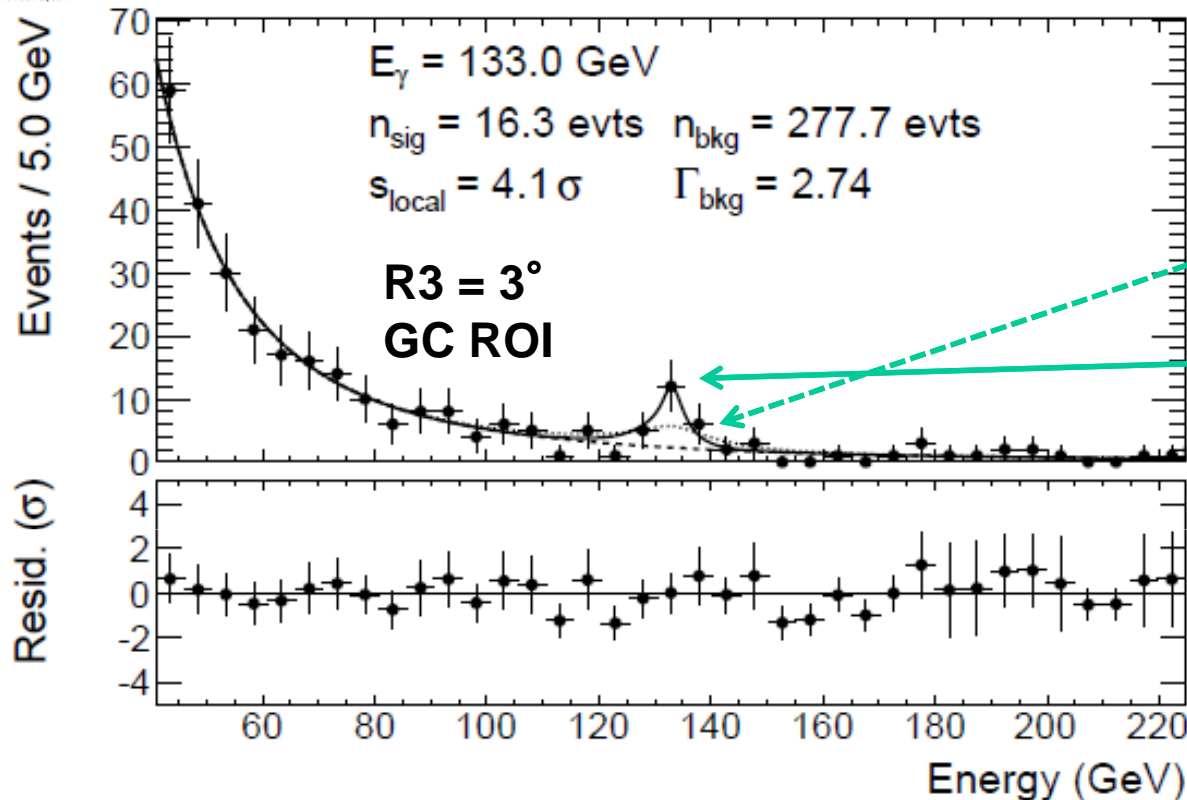


No globally significant fits





# The Line-like Feature near 133 GeV



Dashed is fit with  $s_\sigma=1$

Solid is fit with best fit  $s_\sigma$

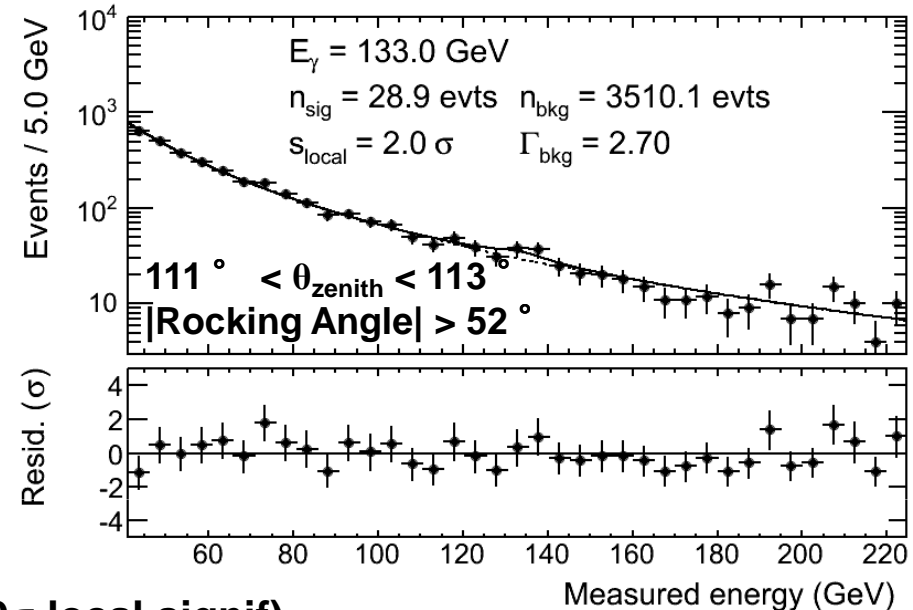
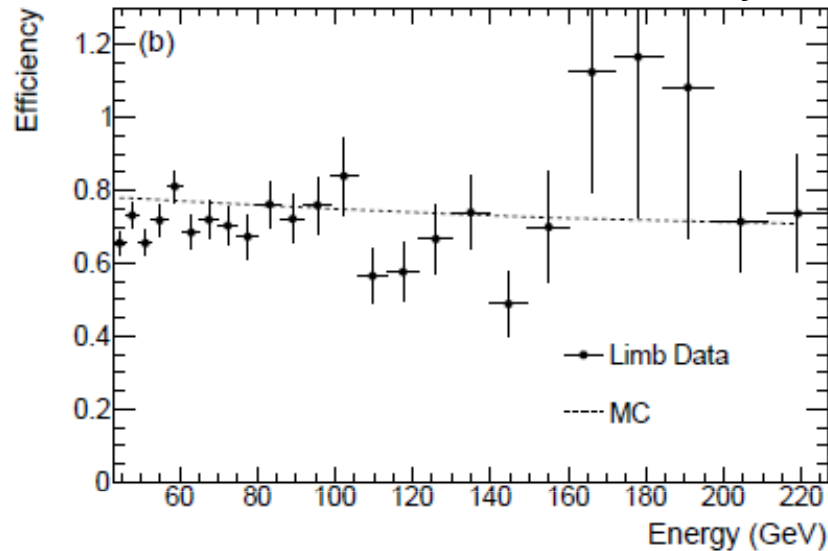
Unbinned fit, binning is for visualization only

- $3.2\sigma$  (local) 2D fit at 133 GeV with reprocessed data
  - Fit with energy dispersion model that includes event-by-event energy recon. quality estimator  $P_E$  (“2D” model)
- Let width scale factor float in fit (while preserving shape)
  - $s_\sigma = 0.32^{+0.22}_{-0.07}$  (95% CL)  $\Delta TS = 9.4$
  - Feature in data is narrower than expected energy resolution ( $s_\sigma=1$ )

# 133 GeV in the Earth Limb spectrum

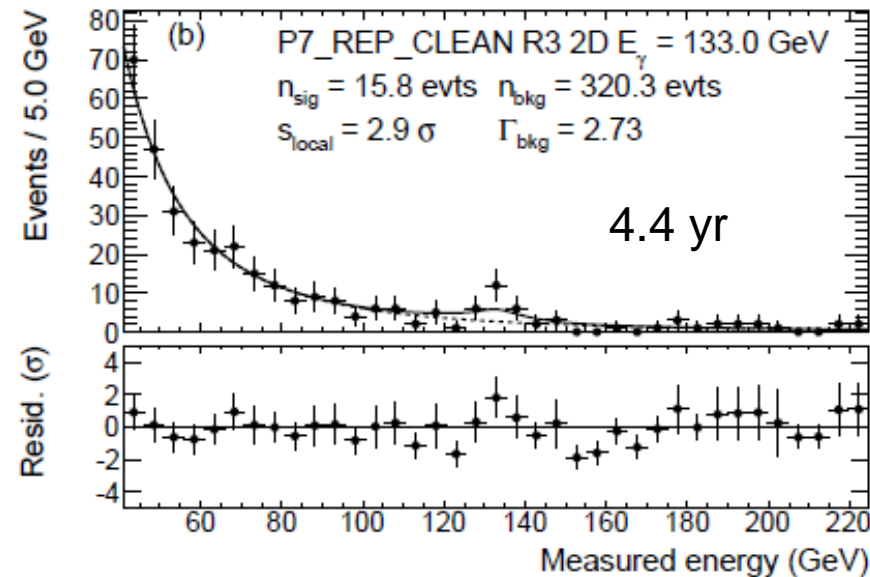
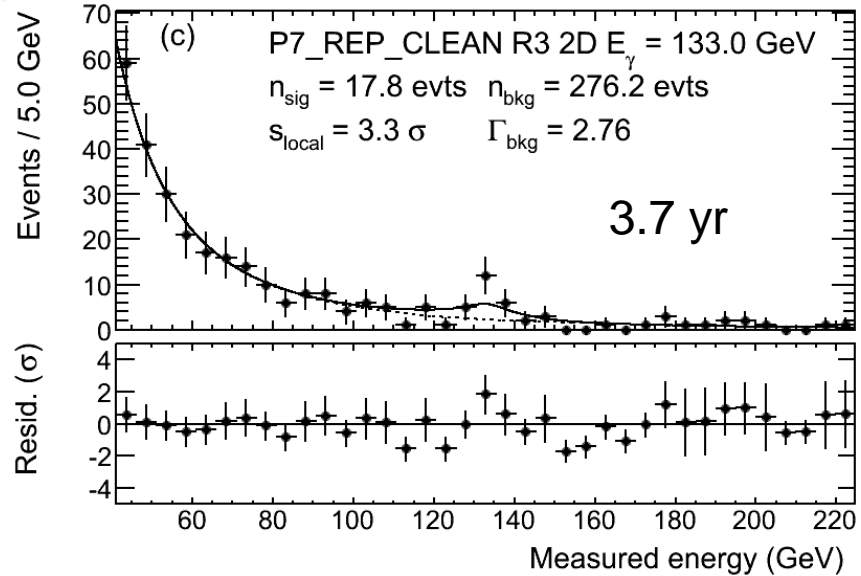


P7Transient to P7Clean Efficiency



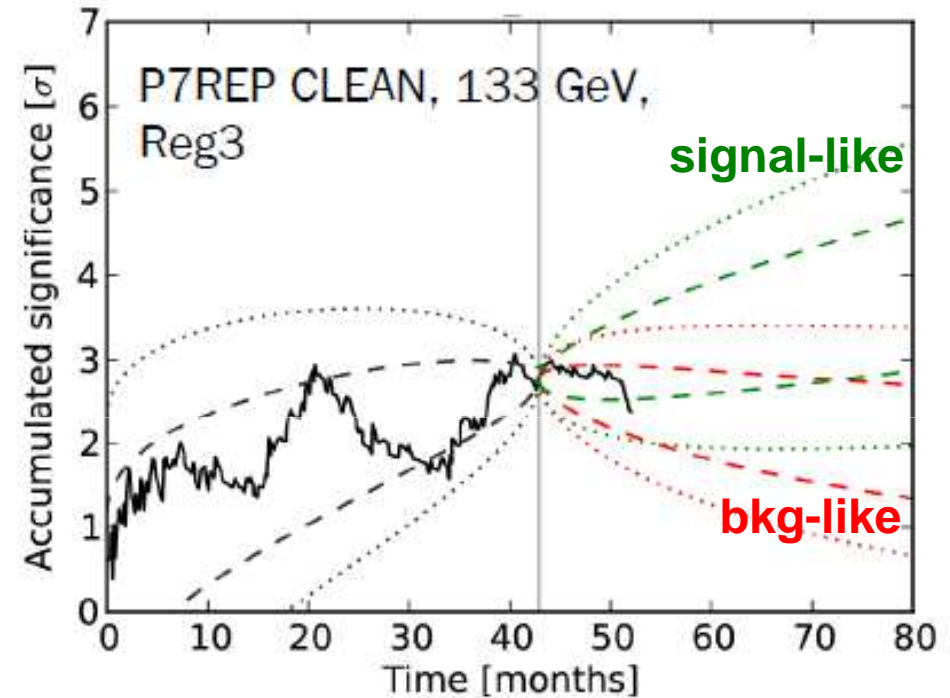
- **Line-like feature in the limb at 133 GeV ( $2.0\sigma$  local signif)**
  - Also reported by others: D. Whiteson (arXiv:1208.3677), A. Hektor et al (arXiv:1209.4548), and D. Finkbeiner et al (arXiv:1209.4562)
  - Appears when LAT is pointing at the Limb ( $|\theta_r| < 52^\circ$ )
  - Surprising since limb should be smooth power-law
  - $S/N_{\text{limb}} \sim 14\%$ , while  $S/N_{R3} 61\%$ 
    - **Limb feature not large enough to directly explain all the GC signal**
- **Dips in efficiency (less stringent Transient cuts -> Clean cuts) below and above 133 GeV**
  - Appear to be related to CAL-TKR event direction agreement
  - Could be artificially sculpting the energy spectrum

# 133 GeV Feature in 4.4 year dataset



Weniger et al (2013)

[http://fermi.gsfc.nasa.gov/ssc/proposals/alt\\_obs/white\\_papers\\_eval.html](http://fermi.gsfc.nasa.gov/ssc/proposals/alt_obs/white_papers_eval.html)



- $s_{\text{local}}$  decreased in 4.4 yr data by ~10% compared to 3.7 yr data
- Since spring 2012, feature has decrease
- More “background-like”



# Summary



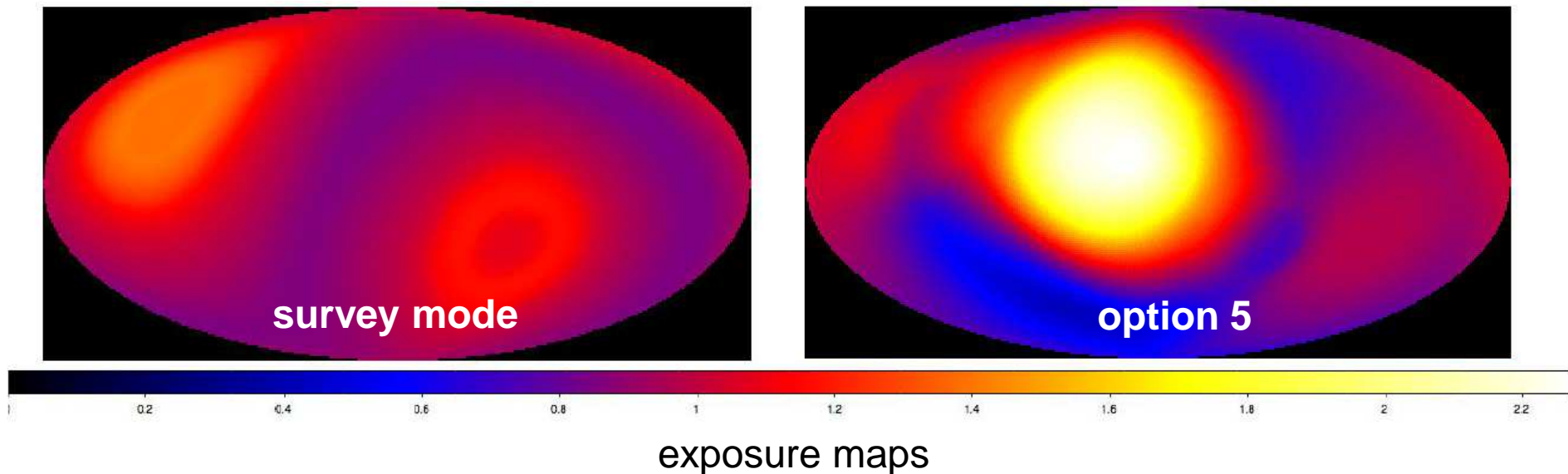
- **Search for DM signal from Milky Way Dwarf Galaxies**
  - Updated 4yr limits are slightly higher than 2yr limits
  - No significant detection
  - Publication in internal review, should be submitted soon
- **Search for spectral lines from 5--300 GeV in 5 ROIs**
  - Submitted for publication in PRD (<http://arxiv.org/abs/1305.5597>)
  - No globally significant lines detected
    - Have set 95% CL  $\Phi_{\gamma\gamma}$ ,  $\langle\sigma v\rangle_{\gamma\gamma}$ , and  $\tau_{\gamma\gamma}$  limits
- **See a narrow residual near 133 GeV in the GC**
  - Not (completely) an obvious systematic error
    - Larger than expected systematic uncertainty
    - Feature in Limb is smaller than GC feature
    - Feature does not appear in inverse ROI
  - Bkg fluctuation?
    - Much narrower than expected energy resolution
    - Decreasing with more data
- **More data and study will improve future LAT analyses**
  - Pass 8  $\rightarrow$  ~25% increase in  $A_{\text{eff}}$  and better (different) systematics

# BACKUP SLIDES

# Modified Observing Strategy



- more info can be found on FSSC  
[http://fermi.gsfc.nasa.gov/ssc/proposals/alt\\_obs/obs\\_modes.html](http://fermi.gsfc.nasa.gov/ssc/proposals/alt_obs/obs_modes.html)
- Panel discussed white paper proposals July 25<sup>th</sup> and recommended a switch to “option 4 or similar” around December 2013.
  - Option 4 points to keep the GC in the field of view, while still providing relatively uniform all-sky coverage
- Public discussion page for community input
  - <https://groups.google.com/forum/#!forum/fermi-observation-strategy-discussion>





# Systematic Effects in each ROI



- **Uncertainties that affect the conversion from  $n_{\text{sig}}$  to  $\Phi_{\gamma\gamma}$** 
  - E.g., exposure uncertainties
  - Do not affect fit significance

- **Uncertainties that scale  $n_{\text{sig}}$** 
  - E.g., modeling energy dispersion
  - Affect significance, but will not induce false signals

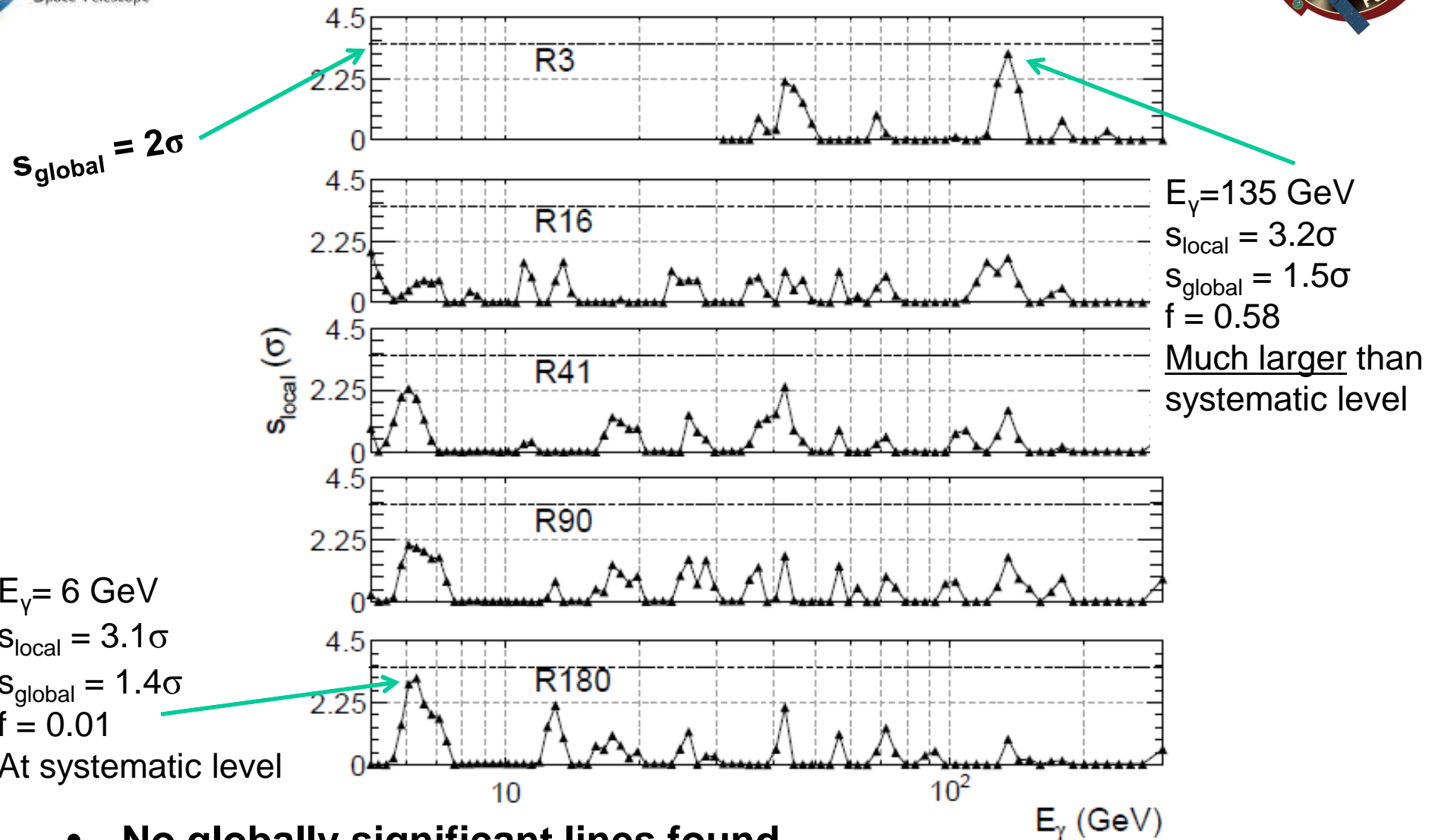
- **Uncertainties that induce or mask a signal**
  - Express as uncertainty in fractional signal,  $\delta f$

	Quantity	Energy	R3	R16	R41	R90	R180
{	$\delta\epsilon/\epsilon$	5 GeV	0.10	0.10	0.11	0.12	0.14
	$\delta\epsilon/\epsilon$	300 GeV	0.10	0.10	0.12	0.13	0.16
{	$\delta n_{sig}/n_{sig}$	All	$\pm_{-0.12}^{+0.07}$	$\pm_{-0.12}^{+0.07}$	$\pm_{-0.12}^{+0.07}$	$\pm_{-0.12}^{+0.07}$	$\pm_{-0.12}^{+0.07}$
{	$\delta f$	5 GeV	0.020	0.020	0.008	0.008	0.008
	$\delta f$	50 GeV	0.024	0.024	0.015	0.015	0.015
	$\delta f$	300 GeV	0.032	0.032	0.035	0.035	0.035

$$TS = 2\ln \frac{\mathcal{L}(n_{\text{sig}} = n_{\text{sig,best}})}{\mathcal{L}(n_{\text{sig}} = 0)} \quad s_{\text{local}} = \sqrt{TS}$$

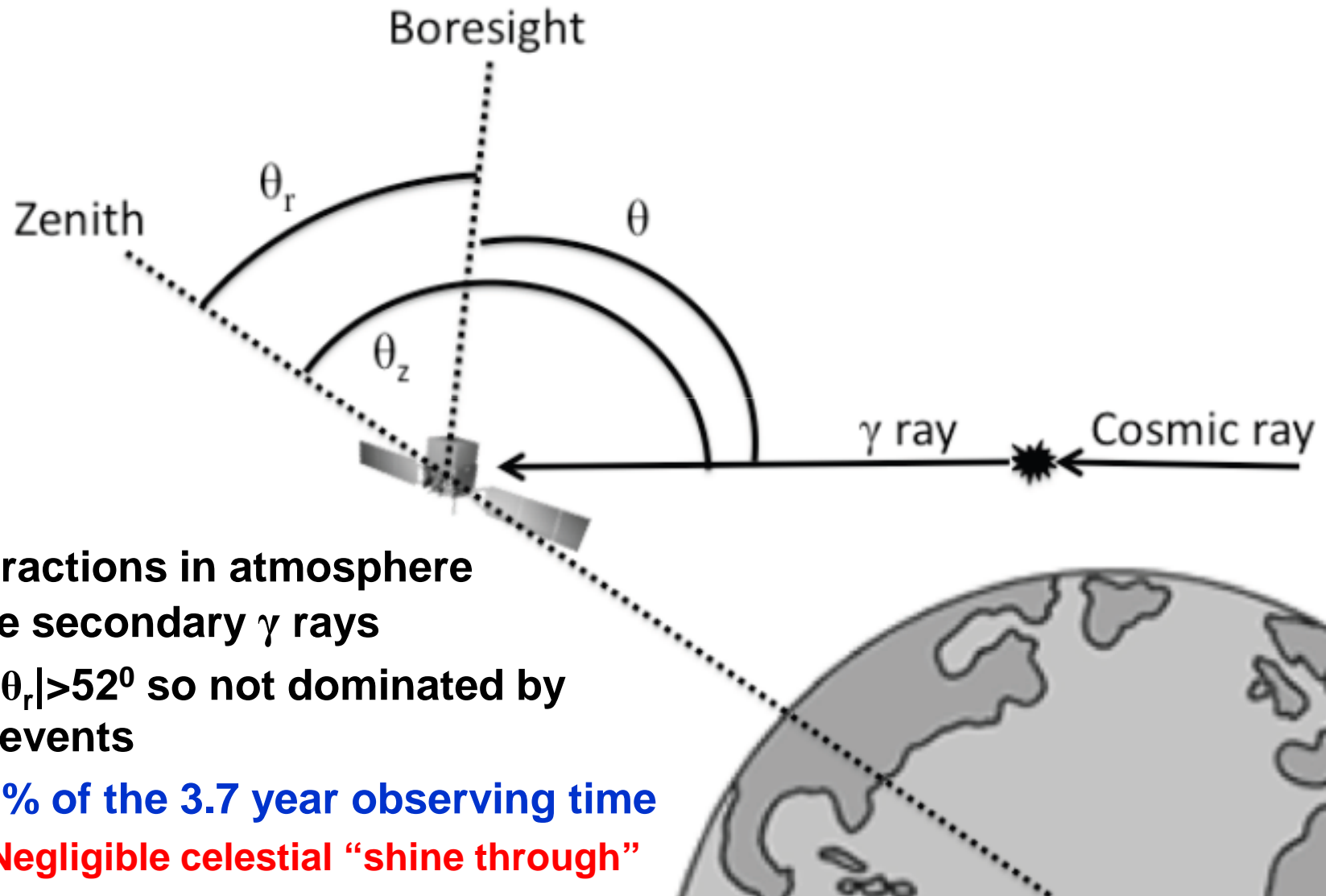
$$f = \frac{n_{\text{sig}}}{b_{\text{eff}}} \simeq \frac{s_{\text{local}}^2}{n_{\text{sig}}}$$

# Fitting Results



- No globally significant lines found

# Earth Limb Control Dataset



- CR interactions in atmosphere produce secondary  $\gamma$  rays
- Select  $|\theta_r| > 52^\circ$  so not dominated by large  $\theta$  events
  - 0.03% of the 3.7 year observing time
    - Negligible celestial “shine through”



# Fitting Method



Predicted Spectrum

Signal Model

Background Model

$$C(E', P_E | \vec{\alpha}) = n_{\text{sig}} D_{\text{eff}}(E', P_E | E_\gamma) w_{\text{sig}}(P_E) + \frac{n_{\text{bkg}}}{c_{\text{bkg}}} \left( \frac{E'}{E_0} \right)^{-\Gamma_{\text{bkg}}} \eta(E') w_{\text{bkg}}(P_E)$$

$$D_{\text{eff}}(E'; E_\gamma) = \int^{FoV} \int^{ROI} D(E'; \theta | E_\gamma) \frac{I_{\text{sig}}(\hat{p}) \mathcal{E}(\hat{p}, \theta, E_\gamma)}{n_{\text{sig}}} d\Omega d\Omega_{\hat{v}}$$

**Effective Energy Dispersion**

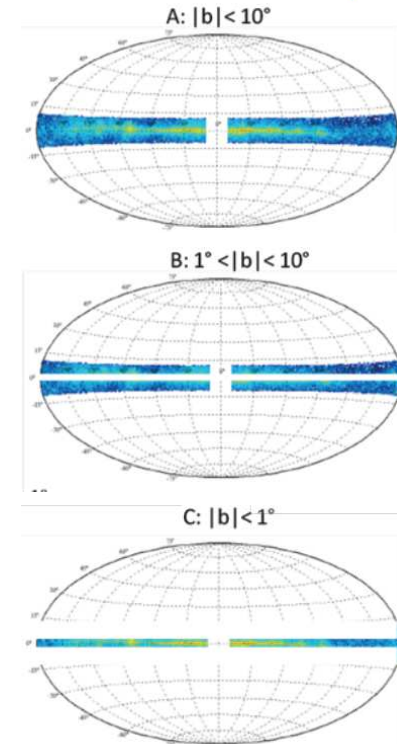
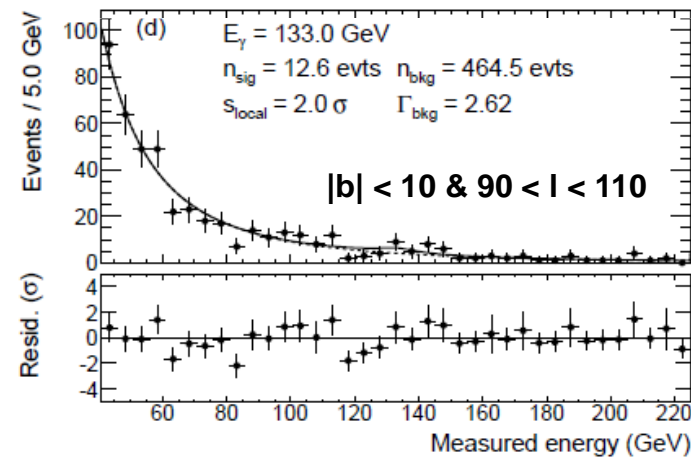
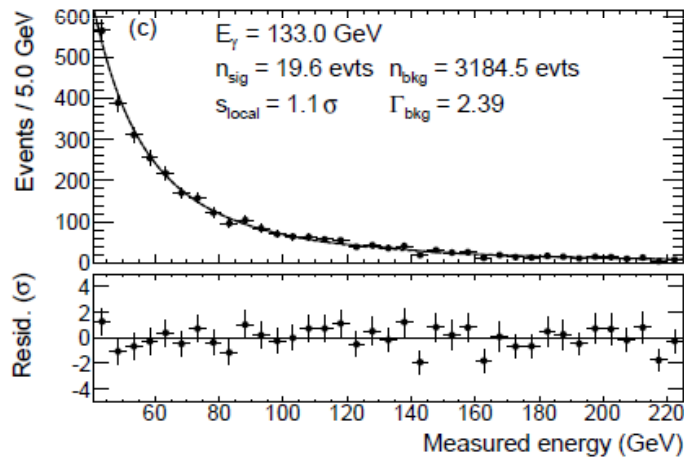
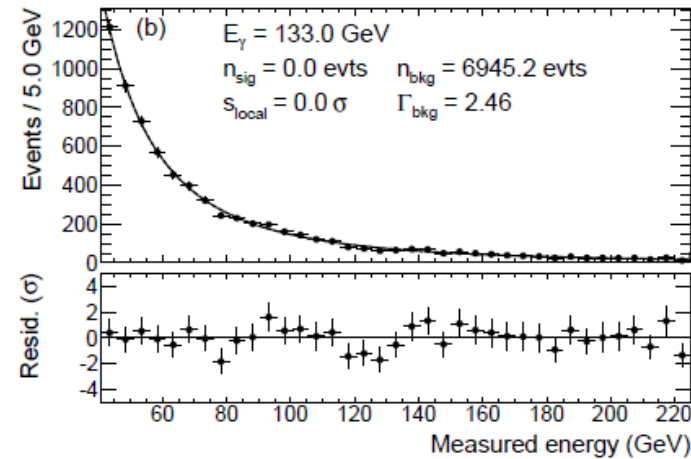
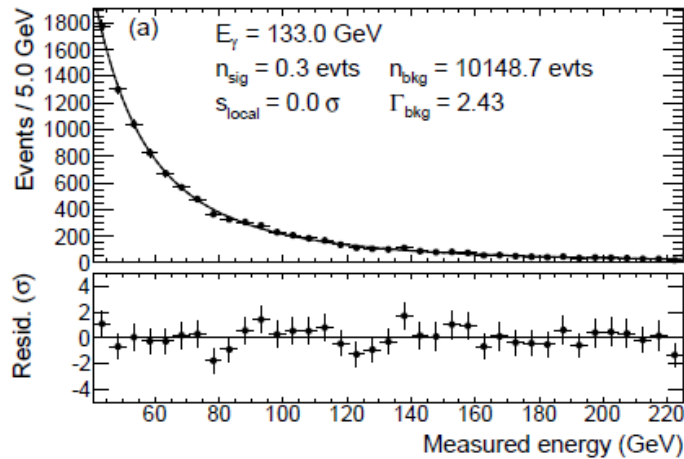
Incorporates energy reconstruction quality ( $P_E$ )

$$\eta(E') = \int^{FoV} \int^{ROI} \frac{I_{\text{bkg}}(\hat{p}) \mathcal{E}(\hat{p}, \theta, E_\gamma)}{n_{\text{bkg}}} d\Omega d\Omega_{\hat{v}}$$

**Effective Area Corrections**

- **Maximum likelihood fit at  $E_\gamma$  in sliding energy window ( $\pm 6\sigma_E$ )**
  - **Fit from 5 to 300 GeV**
  - **$0.5\sigma_E$  steps (88 fit energies)**
- **$n_{\text{sig}}$ ,  $n_{\text{bkg}}$ ,  $\Gamma_{\text{bkg}}$  free in fit**
- **$c_{\text{bkg}}$  is given by normalization of background model**
- **Include  $P_E$  distributions for signal and background:  $w(P_E)$** 
  - **Take from data for each fit (entire ROI and energy fit window)**

# 133 Feature in the inverse ROIs



E. Bloom Fermi  
Symposium 2012

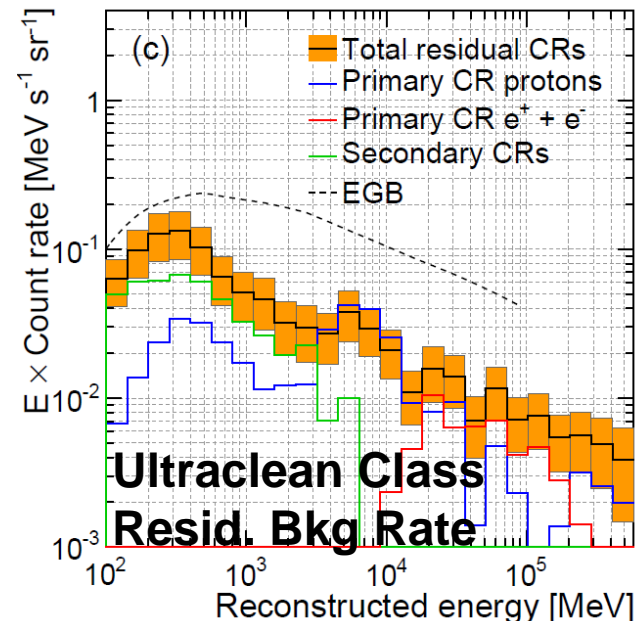
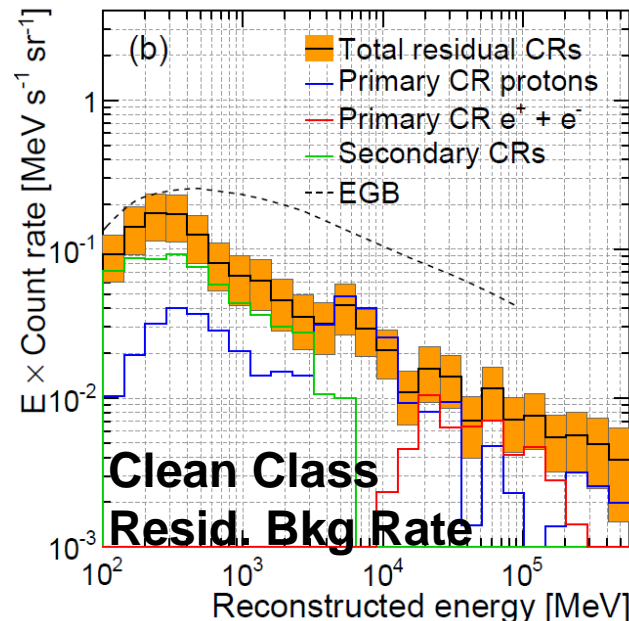
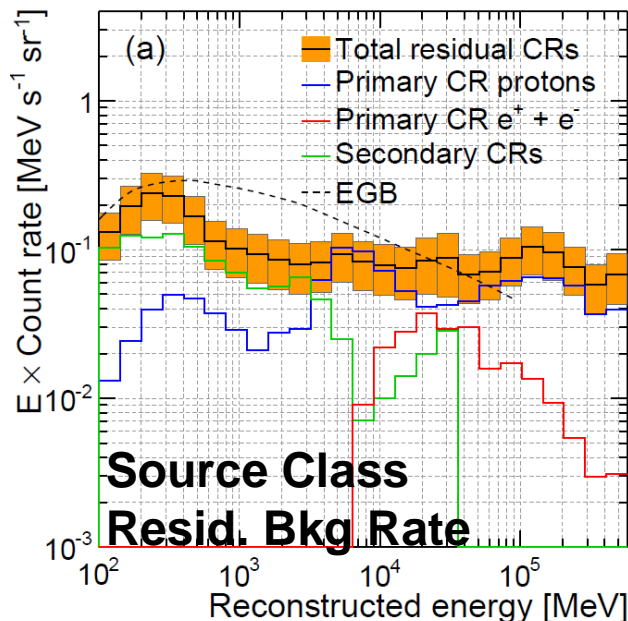
- No obvious feature at 133 GeV in the inverse ROIs
  - Would naively expect an instrumental effect to show up everywhere

# Gamma-ray Event Classes



- Triggered events are dominated by CR background events
  - Need to define additional cuts to get  $\gamma$ -ray rich dataset
- Nested “event classes” for various types of  $\gamma$  ray sources
  - Transient: loosest, for flaring sources (cut in time)
  - Source: moderate, for bright sources (cut in space)
  - Clean: tight, for  $\gamma$ -ray diffuse
  - Ultraclean: tightest, for extragalactic  $\gamma$  rays

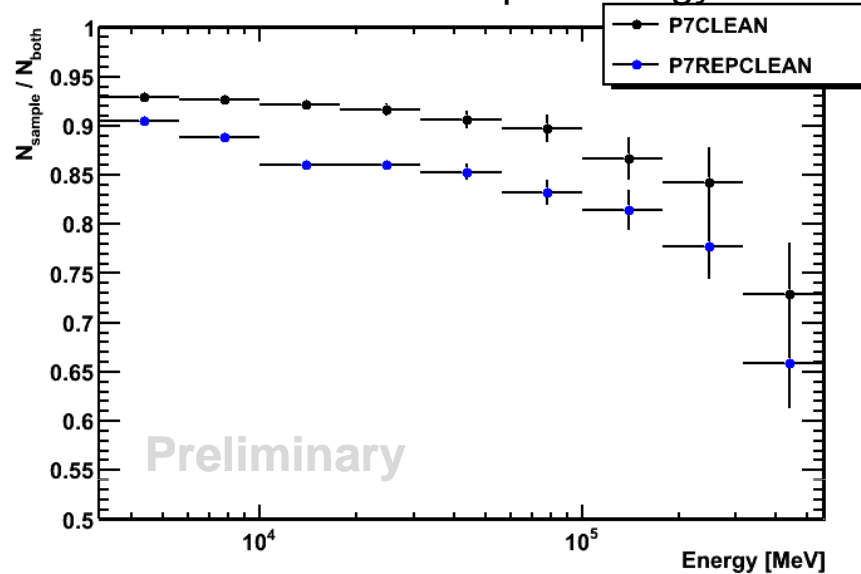
M. Ackermann et al  
(The Fermi LAT  
Collaboration)  
ApJS 203, 4 (2012)  
arXiv:1206.1896



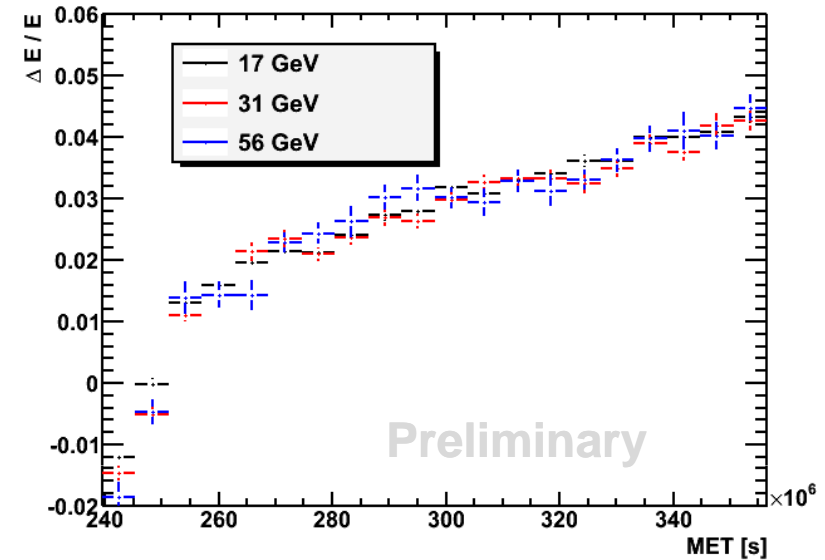
# Data Reprocessing with Updated Calibrations



Event Overlap v. Energy



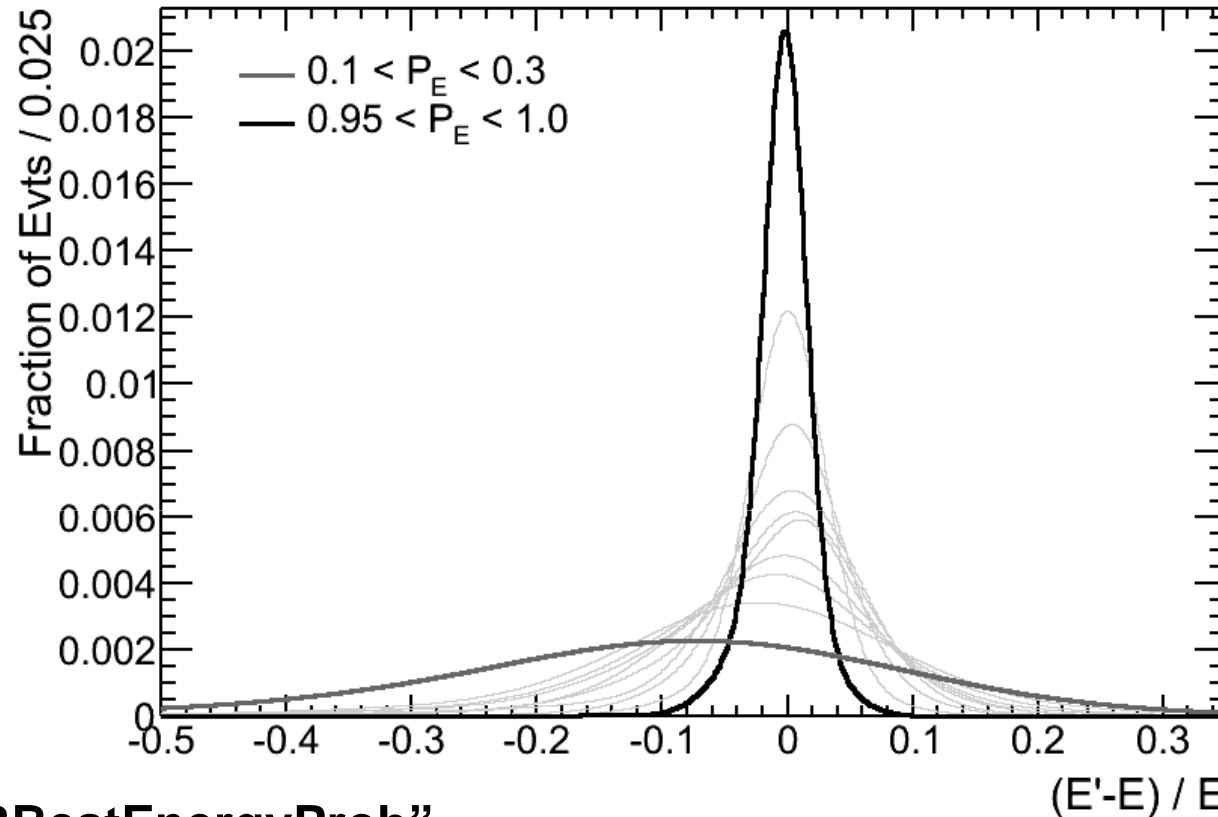
Energy Shift v. Time



- Reprocessing Data with updated calibrations (primarily Calorimeter)
- Improves the agreement between the TKR direction and the CAL shower axis and centroid at high E, improving the direction resolution
- Corrects for loss in CAL light yield b/c of radiation damage (~4% in mission to date)
- 80%+ overlap in events between original and reprocessed samples

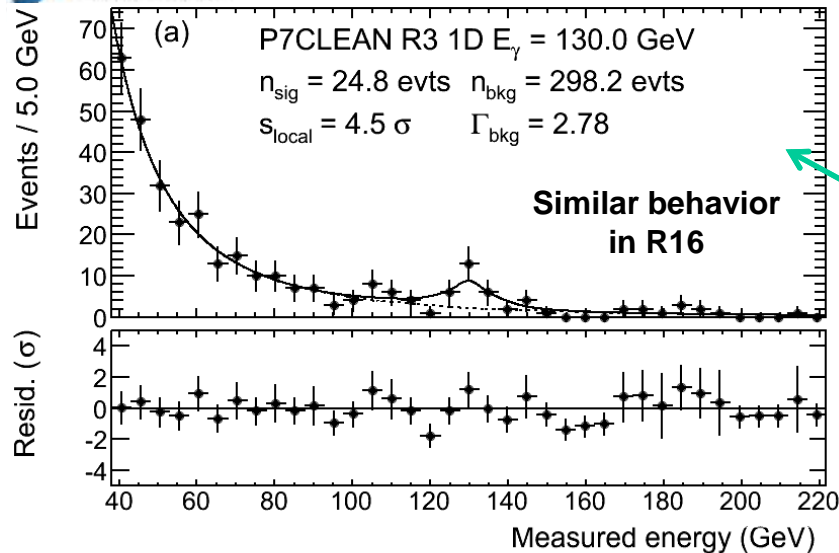


## Energy Dispersion Model (“2D model”)



- $P_E$  = “CTBBestEnergyProb”
  - Probability that the reconstructed energy is within expected 68% containment
- Use triple gaussian model in 10  $P_E$  bins
- Gives ~15% increase in statistical power
  - Similar to adding ~30% more data

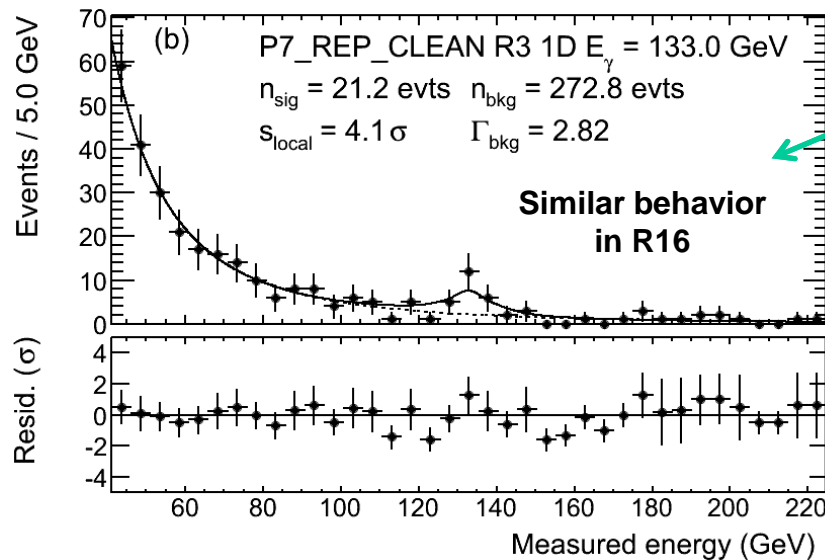
# Studies of Line-like Feature near 133 GeV (1)



- Fits using simpler energy dispersion model
  - no use of energy recon. quality:  $P_E$

- 4.5 $\sigma$  (local) 1D fit at 130 GeV with unreprocessed data

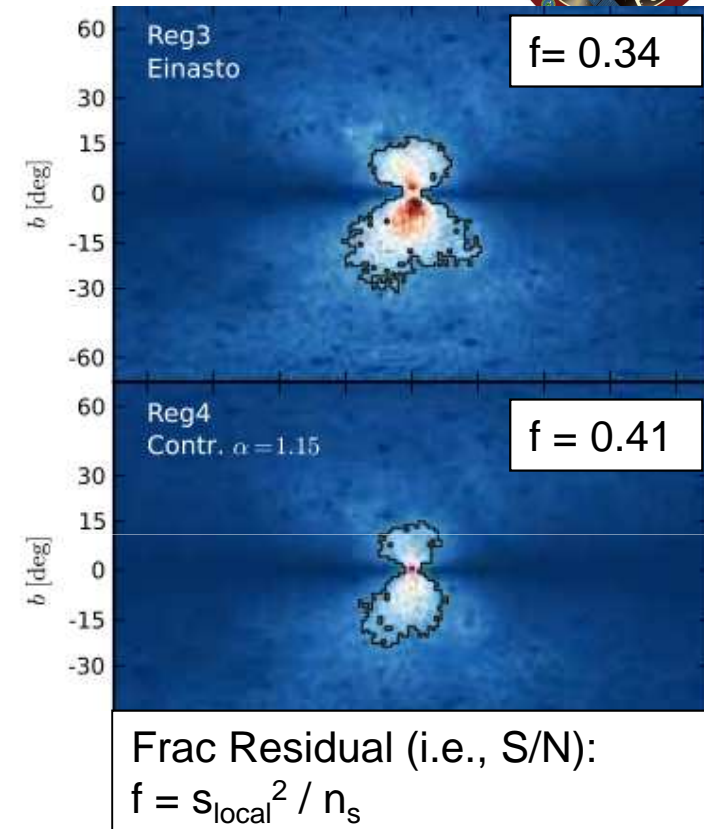
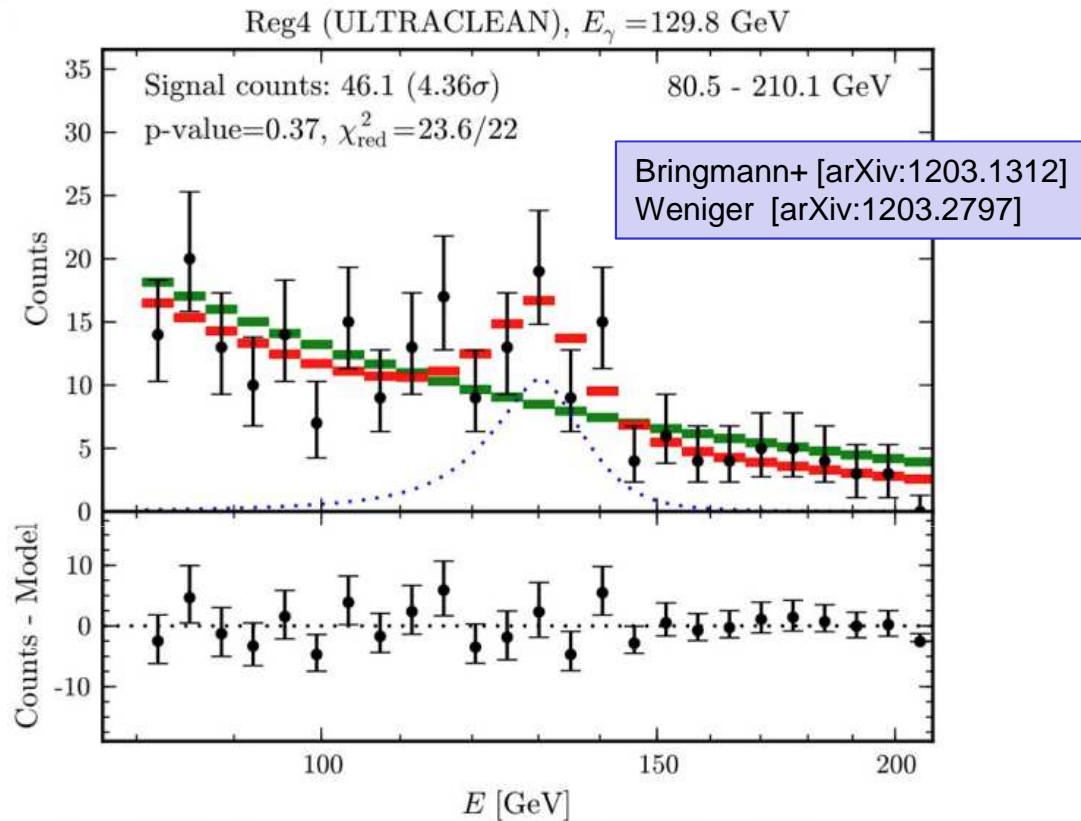
- Comparable to signif. reported in C. Weniger JCAP 1208 (2012) 007  
[arXiv:1204.2797](https://arxiv.org/abs/1204.2797)



- 4.1 $\sigma$  (local) 1D fit at 133 GeV with reprocessed data

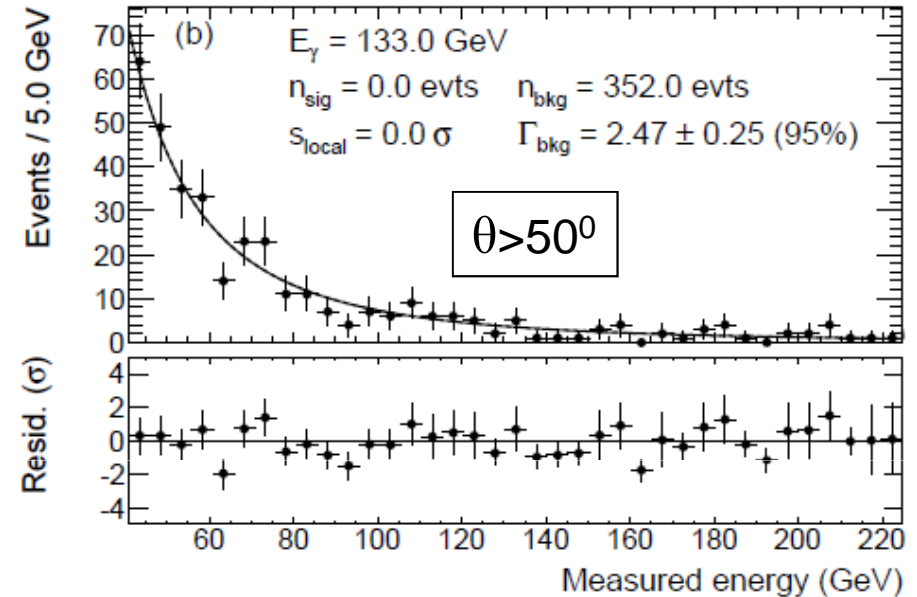
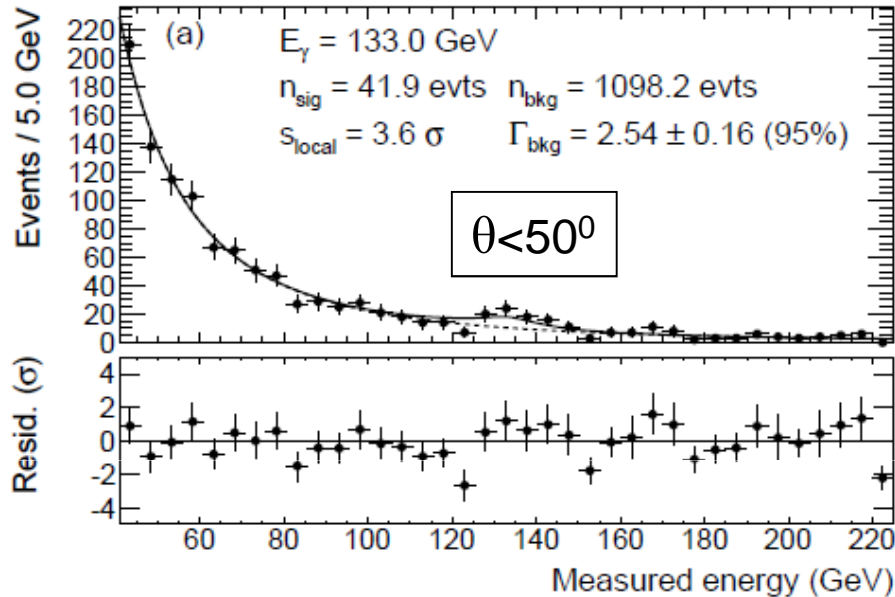
- Shifts higher in energy by a few percent, as expected

# Reported Narrow Feature at 130 GeV (1)



- Bringmann et al. and Weniger showed evidence for a narrow spectral feature near 130 GeV near the Galactic center (GC)
- Signal is particularly strong in 2 out of 5 test regions, shown above
- Over  $4\sigma$ , with S/N > 30%, up to ~60% in optimized regions of interest (ROI)

## $\theta$ -dependence of 135 GeV feature



- Search in a 20x20 GC box (no source removal, 2D model)
- 135 GeV feature appears in low- $\theta$  events, but not in high- $\theta$  events
  - 3.5 $\sigma$  in  $\theta < 50^\circ$  events should scale to 2 $\sigma$  for  $\theta > 50^\circ$  events
- Same behavior observed in the Limb feature